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Population distribution and density of *Antestiopsis thunbergii* (Hemiptera: Pentatomidae) in the coffee growing regions of Rwanda in relation to climatic variables

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ABSTRACT

Antestia bug, *Antestiopsis thunbergii* (Gmelin, 1970) (Hemiptera: Pentatomidae) is one of the most damaging pests of coffee (*Coffea arabica, L.)* worldwide, except in central and south America. A two – year study was conducted to assess the distribution and the density of Antestia bug in the coffee growing regions of Rwanda, and to determine the effects of climatic variables on density of Antestia bug. 205 farms were surveyed in 2016 and 191 farms in 2017. The density and damage of Antestia bug were quantified and climatic variables including temperature, rainfall, wind speed and relative humidity were recorded. Antestia bug was distributed in all coffee growing regions of Rwanda, during both study periods. Over both years, the highest density was recorded in the northern region of the country while the lowest was recorded in the eastern region. The economic damage due to Antestia bug ranged from 0 to 92% and from 0 to 81% in 2016 and 2017, respectively. Stepwise multiple linear regression analysis indicated that temperature and rainfall significantly influenced pest density. However, wind speed was not significantly associated with the density of Antestia bug. Principal component analysis (PCA) indicated three distinct groupings. Coffee regions that received higher, regular rains had a higher population of Antestia bug than where rains were erratic. Similarly, the areas where temperature was consistently high had high densities of Antestia bug. Wind speed was highly and negatively related to principal component one. This study indicated the need to intensify control measures against Antestia bug. Furthermore, the impact of climate change on density and damage of Antestia bug and other coffee pests needs further research.

1. Introduction

Coffee *(Coffea arabica* L.*)* production is critical to the economy of several countries in Africa, Asia, and tropical America (Teodoro et al., 2008). Although there are several constraints to coffee production, including prolonged periods of water stress, low soil fertility in many areas, diseases, and insect pests, Antestia bug is probably the most important (Ahmed et al., 2016). Antestia bug, *Antestiopsis thunbergii* (Gmelin, 1970) (Hemiptera: Pentatomidae), is a direct pest of coffee worldwide, except in central and south America (Babin et al., 2018). Antestia bug is native to Africa but has spread to the coffee growing regions of Asia; such as China, Sri Lanka, Myanmar, Pakistan, and India (Rider et al., 2002). Both the nymph and adult stages of the bug feed on vegetative and fruiting parts of the coffee plant, thereby causing yield loss and negatively affecting quality of coffee beans (Ahmed et al., 2016). When Antestia bug feeds on flower buds, they become black or brown; which impairs fruit set (Mugo, 1994). Feeding on leaves at the growing point results in leaves that are scarred and distorted (Abebe, 1987). Waller et al. (2007) report that Antestia bug causes a significant loss of flowers when it is present in coffee plantations during the onset of rains and severe infestations may prevent the tree from flowering. The economic threshold for Antestia bug is as low as one to two bugs per tree, depending on the damage levels and the country (Mugo et al., 2013). Yield loss due to Antestia bug has been estimated at up to 40% (Le Pelley, 1968).

Antestia bug damage has also been associated with the potato taste defect (PTD) in coffee (Becker et al., 1988; Gueule et al., 2014; Jackels et al., 2014). Potato taste defect is a potato – like smell and taste found in green and roasted coffee beans and in brewed cups of coffee. This defect is an economic concern for producers, because it reduces coffee prices

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paid to farmers and cooperatives. Additionally, international buyers may generally reduce prices they are willing to pay for coffee coming from regions suspected to have PTD, whether or not there is specific evidence of PTD in a given lot of coffee. Although the PTD mechanisms of infection into the coffee beans are not yet known, it has been reported that protection of coffee plantations against Antestia bug reduces the incidence of PTD (Bouyjou et al., 1993).

Climatic variables such as temperature, rainfall, etc. vary in time and space, leading to dynamic effects on pest densities and associated damage (Wallner, 1987). Climatic variables affect insect pests directly, through modification of the physiological or behavioral systems, or indirectly through modification of other factors such as the host plant and natural enemies (Bale et al., 2002). Hodkinson (1999) believes there is a link between climatic variables and pest distribution, specific to every species and dependent on the ecophysiology, which explains the pest's temporal and spatial distribution in a given agro-ecological zone. Amongst climatic variables, temperature plays a direct role in pest distribution and density. For example, Antestia bug survives and develops within a temperature range of 14.6–32.9 °C, but the best growth and reproduction rates are obtained within a temperature range of 19–25 °C (Ahmed et al., 2016).

Similarly, rainy periods influence the distribution and density of insect pests. Liebhold et al. (1993) reported a positive correlation between rainfall levels and grasshopper (*Tettigonia viridissima,* L) densities; however, in the areas that received above-average rainfall, grasshopper populations decreased. Furthermore, rainfall increased psyllid (*Austrochardia acaciae* L) population in the Eucalyptus forests to the extent of causing outbreak of senescence – inducing leaf feeders (Gherlenda et al., 2016). Relative humidity also influences density of insect pests such that, for coffee berry borer (*Hypothenemus hampei*, Ferrari) for example, it accounted up to 9.5% of the variation in pest densities (Teodoro et al., 2008). Additionally, Kirkpatrick (1937) reported that Antestia bug infestations increase with humidity levels in the coffee growing regions of Kenya.

Wind speed and direction also affect the distribution pattern of insects and may cause pest outbreak in some parts of the world (Moser et al., 2009). Williams et al. (2007) suggest that upwind migrations and wind directions may help in pest dispersal. The pollen beetle, *Meligethes aeneus* (Fabricius, 1775) for example was shown to be influenced by the wind speed; it explained about 75% of the variance in the pest density (Moser et al., 2009). Lewis (1969) also showed that *M. aeneus* (Fabricius, 1775), and syrphids, *Eupeodes corolla* (Fabricius, 1794) increased two-to three times in the areas where the wind speed exceeded 2.5 km/h.

Despite the availability of climatic data and massive yield losses and coffee quality issues that Antestia bug causes, particularly through the association with the potato taste defect, there is currently no information available on Antestia bug density and distribution in Rwanda; and how they relate to climatic variables. The objectives of this study were twofold: (i) to evaluate the density and the distribution of Antestia bug in the coffee growing regions of Rwanda, (ii) to determine the effects of climatic variables on the density of Antestia bug.

2. Materials and methods

2.1. Study site

This study was conducted in all the coffee growing regions of Rwanda: Central Plateau and Granitic Ridges in the North, Mayaga, Bugesera and Eastern savannah in the East and Congo Nile Watershed Divide and Impala in the West. Surveyed farms were selected using stratified random sampling from the list of coffee growers held by the Rwanda National Agriculture Export Development Board (NAEB). 205 farms were surveyed in the first year and 191 in the second year. In 2016, we sampled 73 farms in the West, 69 in the South, 35 in the East and 28 in the North while in 2017, we sampled 68 in the North, 65 in the South, 33 in the East and 25 in the North. The altitude of surveyed farms ranged from 1381 to 2135 m above sea level (masl). The study was conducted from March to July 2016 and May to July 2017. In the study, we collected information about the age of the coffee plantations, whether the plantation was weeded or whether pesticide was applied and at which dates. We also recorded if shade trees or intercrops were used and whether the coffee bushes were pruned. The requirements for farm selection were threefold: (1) the farm was bearing at the time of the survey, (ii) the field was sufficiently large to obtain 30 plants along the diagonals and (iii) farms were at least 7 km distant one from the other, to reduce the chances of auto-correlation among farms (Overmars et al., 2003).

2.2. Assessment of pest density and damage

At each farm, 30 coffee bushes were assessed along two transects (15 plants each) for the presence or absence of Antestia bug. For each selected coffee tree, we assessed Antestia bug density through direct counting, by observing the coffee tree for 5 min and counting the number of Antestia bugs present. This method of assessing Antestia bug density through direct count has been previously used by Bigirimana et al. (2019) and Ahmed et al. (2016) and is effective because Antestia bug is relatively a big insect. Surveys were mostly conducted in the morning (from 7:00–11:00 a.m.) and afternoon hours (2:00–6:00 p.m.) to record the maximum number of Antestia bug.

To determine infested berry density, three bearing branches (one at the bottom, middle, and top of the tree) were sampled. Assessment of damage density was done using damage symptoms where coffee beans infested by Antestia bug had lateral holes on the berries (Bigirimana et al., 2019). The total number of berries per branch along with those infested by Antestia bug were counted. Altitude in meters above sea level (masl) was recorded using a Ground Positioning System (Thommen Altitronic) at a central point for each farm surveyed.

2.3. Climatic variables

Climatic variables, i.e. temperature, rainfall, wind speed, and relative humidity, were obtained from weather stations across the coffee growing regions of Rwanda. The number of weather stations in the coffee growing areas varied between agricultural zones. In the Eastern region, we used climatic data from Kirehe and Ngoma weather stations. Kirehe is located in Kirehe district, at latitude of −1.968 S, longitude of 30.137 E and altitude of 1481 masl while Ngoma is located in Ngoma district, at latitude of −1.968 S, longitude of 29.53 E and altitude of 1602 masl.

In the Southern region, we used data from Rubona and Byimana weather stations. Rubona is located in Huye district, at a latitude of −1.58 S, longitude of 29.89 E and altitude of 2396 masl while Byimana is in Ruhango district, at latitude of −1.968 S, longitude of 30.137 E and an altitude of 2396 masl. In the Western region, we used data from Kamembe, Nyamasheke and Rubengera weather stations. Kamembe is located in Rusizi district, at latitude of −1.68 S, longitude of 29.26 E and altitude of 1556 masl, Nyamasheke weather station is in Nyamasheke district, at latitude of −2.34 S, longitude of 29.09 E and altitude of 1471 masl while Rubengera is in Karongi district, at an altitude of 1700 masl, latitude of −2.07 S and longitude of 29.42 E. Climatic data from the weather stations closest to the farms surveyed were used in the study. In most cases, we used climatic data on surveyed farms from weather stations located in the same regions. Because variations in climatic data among weather stations were small, we used average monthly data per each variable for each year of the study in both 2016 and 2017.

2.4. Statistical analysis

The percentage berries infested by Antestia bug along with the bug density were averaged for each farm surveyed. Mean climatic data were also calculated for monthly measurements of temperature, rainfall,

relative humidity and wind speed. To test whether Antestia bug density and damage were significantly different between agricultural zones, we used one-way analysis of variance (anova) for both variables. Fixed effects were bug density and damage, respectively while random effects were different regions. Replications were the number of farms surveyed per region. To this end, the percentage infested berries and the bug density were subjected to the normality test using Shapiro Wilk test and the homogeneity of variance test using Levene's test. The one-way ANOVA test was followed by Tukey's multiple comparison procedure at $P = 0.05$.

We also used the stepwise multiple regression analysis to assess the influence of climatic variables on the density of Antestia bug in the coffee growing regions of Rwanda using the following model:

$$Y = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \varepsilon \quad (1)$$

Where Y is the bug density, α : the intercept, β_1 the coefficient of temperature (X1), β_2 the coefficient of rainfall (X_2), β_3 the coefficient of windspeed (X_3) and β_4 the coefficient of relative humidity (X_4) and ε is the error term. Model selection was done using Bayesian Information Criterion and the model with the smallest (BIC) was selected (Aho et al., 2014).

Given that climatic variables were inter-related, a phenomenon that could be predicted because of the nature of the climatic data, for example rainfall and relative humidity, we sought to identify the ones that explained the most variations. To this end, we used Bartlett's test of sphericity to test the null hypothesis that the correlations among climatic variables were zero or that the correlation matrix was an identity matrix (Raykov and Marcoulides, 2008) for both the climatic data and Antestia bug density in both 2016 and 2017. We observed that Bartlett's test was significant ($\chi^2 = 577.603$, DF = 10, $P < 0.000$) which indicated that the climatic variables and the Antestia bug density in 2016 were related. We also subjected the same data set to Keiser – Meyer – Olkin (KMO) measure of sampling adequacy and observed that KMO was equal to 0.627. Both the Bartlett test and KMO index indicated that the data set in 2016 was appropriate for Principal Component Analysis (PCA).

We also used Bartlett's test and KMO index for the data set in 2017 and similar to 2016, we observed that the Bartlett test was significant ($\chi^2 = 707.694$, DF = 10, $P < 0.000$) and that the KMO was equal to 0.664. Both Bartlett's test and KMO index indicated that the data set in 2017 was also appropriate for PCA. Both data sets were then analyzed using PCA and relationships between climatic variables, locations, and Antestia bug densities were visualized using the PCA score plots. Statistical analyses were conducted using SAS (Version 9.4, SAS Institute, Cary, North Carolina, USA).

3. Results

3.1. Antestia bug distribution across the coffee growing regions of Rwanda

In both 2016 and 2017, Antestia bug was found in all the coffee growing regions of Rwanda. In 2016, the density ranged from 0 to 8 with a mean density of 0.75 ± 0.19 (Mean ± SE) Antestia bugs per tree. We found significant differences between locations for Antestia bug density ($F = 9.36$, DF = 3, 20, $P < 0.01$) during 2016. The highest density was recorded in the North with the mean of 1.46 ± 0.28 bugs per tree and the lowest in the East with the mean density of 0.27 ± 0.04 bugs per tree (Fig. 1).

Similarly, significant differences were observed between locations in 2017 ($F = 27.09$, DF = 3, 20, $P < 0.01$). Consistent with the first year, the highest density of Antestia bug was recorded in the North, with a mean density of 1.72 ± 0.11 Antestia bugs per tree and the lowest in the East with a mean density of 0.58 ± 0.04 Antestia bugs per tree. The exception was in the West where the density was 0.84 ± 0.15 Antestia bugs per tree in 2016 and decreased to 0.43 ± 0.16 Antestia bugs per tree in 2017. Additionally, in 2017, the bug density ranged from 0 to 9 Antestia bugs per tree with an overall mean density of 0.67 ± 0.24.

3.2. Antestia bug damage across the coffee growing regions of Rwanda

Results indicated that Antestia bug damage was higher in 2017 compared to 2016 in all coffee growing regions of Rwanda except in the East (Fig. 2). In 2016, significant differences were observed between regions in berry damage by Antestia bug ($F = 10.52$; DF = 3, 8; $P < 0.01$).

The percent berry damage ranged from 0 to 92% damaged coffee beans with a mean of 4.39 ± 0.69. The highest berry damage was recorded in the East with a mean damage of 7.51 ± 0.83 percent damaged coffee beans and the lowest in the South with a mean damage of 2.93 ± 0.40 percent damaged coffee beans (Fig. 2).

Significant differences in berry damage caused by Antestia bug were also observed between locations in 2017 ($F = 10.65$, DF = 3, 8, $P < 0.01$). The highest berry damage was recorded in the North, with a mean of 11.97 ± 0.45 percent damaged coffee beans and the lowest in the East, with a mean of 3.78 ± 0.67 percent damaged coffee beans. The percent damaged beans ranged from 0 to 81% with a mean of 11.05 ± 0.16 across the country. The percent berry damage by Antestia bug was higher in 2017 compared to 2016 in all the three locations

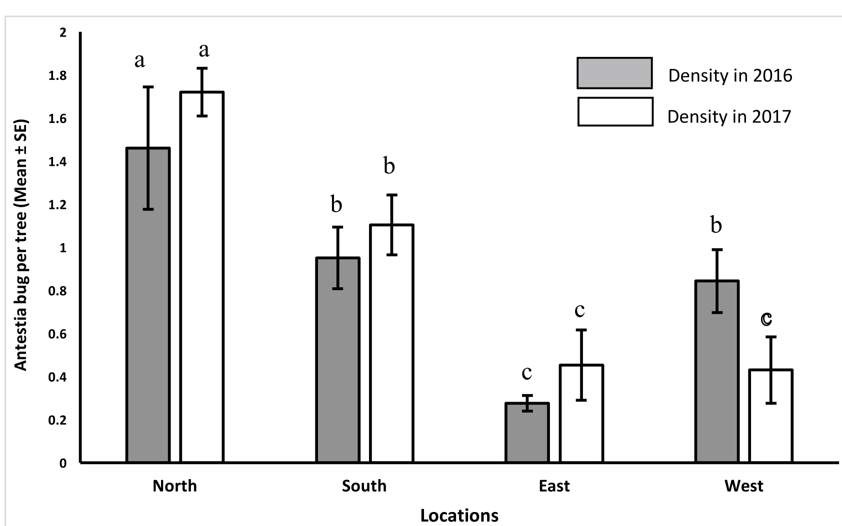

Fig. 1. Antestia bug density indifferentcoffee growing regions of Rwanda. Bars represent the standard error of means.

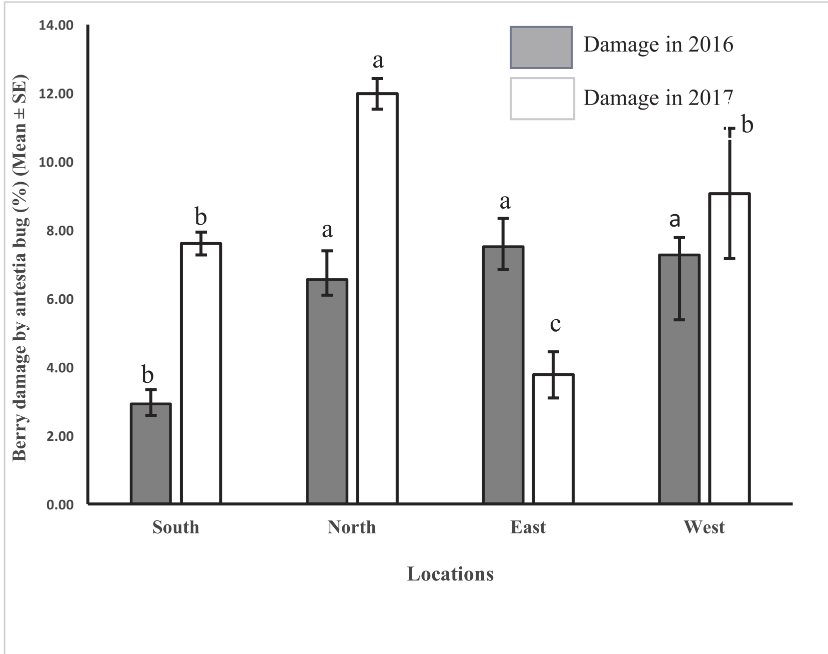

Fig. 2. Percent berry damage by Antestia bug in different coffee growing regions of Rwanda. Bars represent the standard error of means.

except in the East, with a mean of 3.71 ± 0.67 in 2017 compared to 7.51 ± 0.83 in 2016.

3.3. Relationships between climatic variables and Antestia bug density

The multiple linear regression model with the smallest Bayesian Information Criterion (BIC = 814.879) in 2016 accounted for 31.5% of the variability in Antestia bug density as a function of climatic variables. In this model, variables including temperature (P = 0.0008), rainfall (P = 0.0001) and relative humidity (P < 0.0001) significantly increased Antestia bug density (Table 1).

In 2016, only wind speed did not significantly influence bug density in the coffee growing regions of Rwanda (P = 0.0571). Increase in temperature and relative humidity led to increased Antestia bug densities. However, rainfall was negatively related to the Antestia bug density.

Similar to 2016, the model selected in 2017 for multiple linear regression with the smallest BIC (715.18) accounted for 29.6% of the variability in Antestia bug density as a function of climatic variables. In 2017, variables including temperature (P < 0.05), rainfall (P < 0.01) and relative humidity (P < 0.01) significantly increased Antestia bug density (Table 1). Consistently with the previous year, wind speed did not significantly affect the bug density (P > 0.05). Results also indicated that an increase in temperature and relative humidity led to increased bug densities. However, rainfall was negatively related to Antestia bug density.

The principal component analysis indicated that the first and the second principal components (PC) accounted for 52.74% and 22.88% of the variance respectively (Fig. 3). Wind speed was highly and negatively related to the PC1. However, temperature was positively and highly

Table 1
Stepwise regression of climatic variables on density of Antestia bug in the coffee growing regions of Rwanda.

Variable	Year 1			
	Par. estimate	Stand. error	t Value	Pr > F
Intercept	124.367	36.734	11.46	0.0009**
Wind speed	1.136	0.594	3.66	0.0571^{ns}
Temperature	6.636	1.943	11.66	0.0008**
Rainfall	0.187	0.048	15.28	0.0001**
Relative humidity	1.122	0.141	63.02	<.0001**
Variable	**Year 2**			
	Par. estimate	Stand. error	t Value	Pr > F
Intercept	6.854	7.555	−0.91	0.3655^{ns}
Temperature	6.034	2.696	2.24	0.0264*
Rainfall	0.021	0.007	−3.07	0.0024**
Wind speed	0.560	0.407	−1.38	0.1706^{ns}
Relative humidity	0.046	0.017	2.71	0.0073**

Parameters whose P values are marked with * indicate significance at P < 0.05 and those marked with ** indicate significance at P < 0.01.

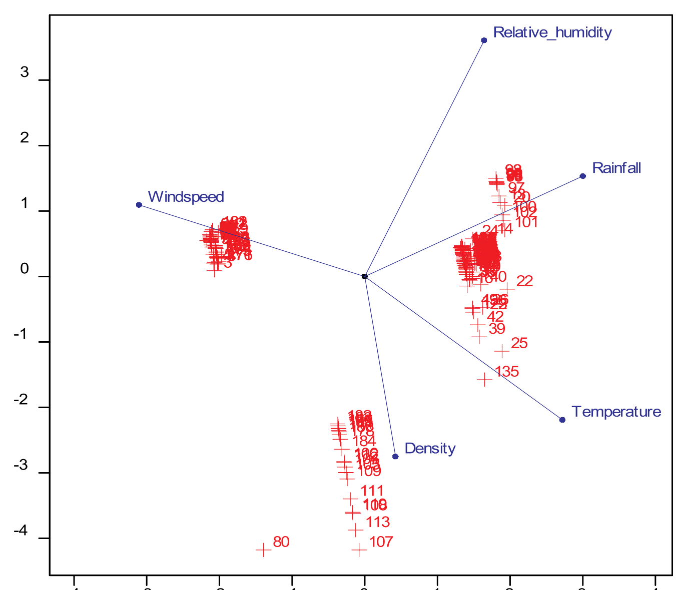

Fig. 3. Biplot from principal component analysis of 205 samples collected across the coffee growing areas of Rwanda; recorded variables were Antestia bug density, temperature, rainfall, relative humidity and wind speed. Dots represent data points. The first and the second component accounted for 52.74% and 22.88% of the total variation, respectively.

correlated with PC1 (Table 2). Other climatic variables such as rainfall and relative humidity were positively and highly correlated with PC2 (Table 2).

The correlation between Antestia bug density and windspeed was positive and significant ($r = 0.15$, $P < 0.05$). However, rainfall, temperature and relative humidity were positively related to Antestia bug density to varying degrees. The correlation between Antestia bug density and rainfall was positive and significant ($r = 0.23$, $p < 0.05$). Similarly, the correlation between temperature and Antestia bug density was positive and significant ($r = 0.17$, $p < 0.05$). In contrast, the correlation between relative humidity and Antestia bug density was moderate ($r = 0.47$, $p < 0.01$).

Climatic variables and Antestia bug density in different regions were grouped differently using PCA. This was suggested by our field observations. For example, coffee regions that received higher, regular rains had a higher population of Antestia bug than where rains were erratic. Similarly, the coffee growing areas where temperature was consistently higher had higher densities of Antestia bug. There were three clear distinctions in the data set (Fig. 3), possibly resulting from different regions where sampling was done. Antestia bug densities in the East and in the West were different, as were also the climatic variables. However, there was no clear difference between the North and the South in the above parameters.

During the second study year, the principal component analysis showed 57.79% of the variations were explained by PC1 and 29.25% by PC2 (Fig. 4). Consistent with year 1 of the study, wind speed was highly and negatively related to PC1 and temperature was highly but positively related to PC1. Other climatic variables such as rainfall and relative humidity were positively related to PC2. Density was highly correlated with PC2 (Table 2).

The correlations between climatic variables and Antestia bug densities varied to some degree. The correlation between Antestia bug density and relative humidity was high ($r = 0.57$, $p < 0.05$).

Similarly, the correlation between rainfall and Antestia bug density was high ($r = 0.59$, $p < 0.05$). However, the correlation between the wind speed and Antestia bug density was weak and negative (- 0.18, $p < 0.05$). Principal Component Analysis showed two distinct groupings – (i) the regions that received higher rains and with higher temperatures had high density of Antestia bug and (ii) the regions where the wind speed was high also had high Antestia bug densities (Fig. 4).

4. Discussion

The study showed that Antestia bug is distributed throughout the country with the highest densities in the Northern region. It has been reported in Rwanda since 1959 (Foucart and Brian, 1959; Babin et al., 2018) and it appears to be an established coffee pest in the country because the climatic conditions are favorable. This is the first study conducted to assess the distribution and density of this pest in the country. Although Antestia bug egg parasitoids such as *Scelioninae Gryon fulviventre* (Crawford) and *Hadronotus antestiae* (Dodd) were reported in East Africa (Babin et al., 2018), we could not find such egg parasitoids in the study area. Additionally, the study was conducted before harvest, the time when most coffee farms were not pruned and therefore we could not evaluate the effects of pruning on the bug density. However, it has been reported that pruning opens up the coffee bushes and thus creates unfavorable conditions for Antestia bug while also improving pesticide penetration and efficacy (Bigirimana et al., 2012). Furthermore, most coffee farms that were sampled in the study were grown in the open sun and hence, we could not evaluate the effect of shade trees and intercropping on Antestia bug density.

Table 2
Principal component loadings for the first two principal components for both study years. The correlation between the variable and the principal component is indicated in bold.

Climatic variables	Year 1		Year 2	
	PC1	PC2	PC1	PC2
Temperature	**0.922**	0.191	**0.961**	−0.082
Rainfall	0.448	**0.845**	0.66	**0.698**
Wind speed	**−0.817**	−0.502	**−0.936**	−0.245
Relative humidity	−0.166	**0.908**	0.169	**0.848**
Density	**0.426**	−0.161	−0.052	**0.901**

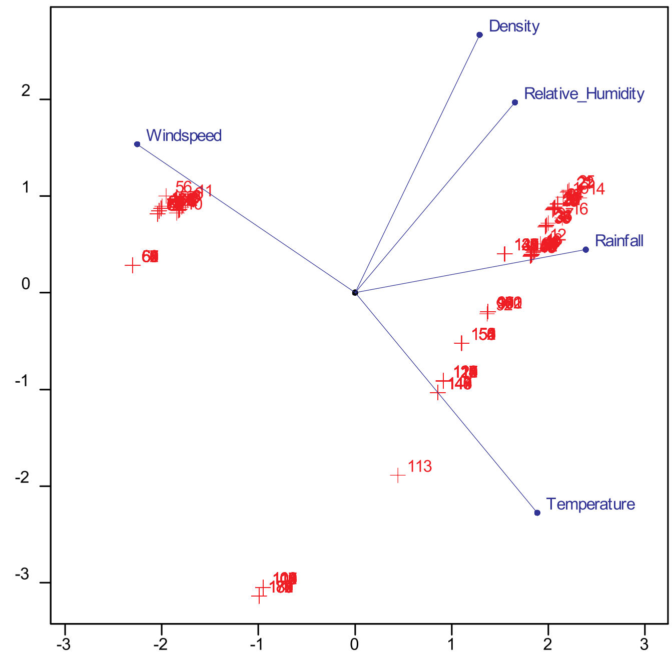

Fig. 4. Biplot from principal component analysis of 191 samples collected across the coffee growing areas of Rwanda; recorded variables were Antestia bug density and climatic variables were temperature, rainfall, relative humidity and wind speed. Dots represent data points. The first and the second component accounted for 57.79% and 29.25% of the total variation, respectively.

The highest density of Antestia bug in the North may be explained by the prevailing climate in the region. Most coffee growing areas in the North are located in the Central Plateau and Granitic Ridges, an agro-ecological zone with the highest temperature among the coffee growing regions of Rwanda (Verdoodt and Van Ranst, 2003; Bigirimana et al., 2019). Temperature substantially shortens the time it takes Antestia bug to complete a life cycle and thus higher temperatures contribute to increased generations of this pest (Ahmed et al., 2016).

Antestia bug density was consistently higher in 2017 in all regions than in 2016 except in the West where the pest population was reduced. This can possibly be attributed to greater rainfall in this region than in the other coffee growing areas. These findings agree with Kirkpatrick (1937) who observed high density of Antestia bug in the moist areas. The study also showed that Antestia bug damage was consistently higher in 2017 than in 2016 in all areas except in the East. This can possibly be explained by pest competition. Hughes and McKinlay (1988) reported that pest species with a patchy distribution, such as Antestia bug, sometimes cause irregular losses that decrease with increased pest densities.

Antestia bug density was positively and significantly related to temperature, rainfall and relative humidity. This finding agrees with Ahmed et al. (2016) who reported that optimum temperature for Antestia bug development ranges from 20 to 25 °C and that beyond 35 °C, pest development slows down. Furthermore, Kirkpatrick (1937) reported that Antestia bug density increases with relative humidity in the coffee growing regions of Kenya.

Principal component analysis grouped the coffee growing regions, climatic data and Antestia bug density into three separate clusters in

2016 - (i) climatic variables and Antestia bug density in the East, (ii) climatic variables and Antestia bug density in the West and (iii) climatic data and Antestia bug density in the South and the North combined. Grouping the North and the South together may be explained by similar climatic characteristics in both regions. Variations in climatic variables such as rainfall, relative humidity and temperature in both regions were similar and the bug densities were closely related. Zitko (1994) reported that PCA is helpful in displaying temporal and spatial relationships between related variables.

In 2017, PCA grouped climatic data and the pest density in two separate groups – (i) the pest data and climatic variables in the West, (ii) the pest density and climatic variables in the South and the North combined while the East was scattered in the PCA score plot. Scattering of pest and climate data from the East in the PCA score plot may be explained by low values in Antestia bug density and climatic variables, particularly the wind speed, the rainfall and the relative humidity. Principal component analysis grouped pest and climatic data in 2016 into three groups and those in 2017 into two groups based on similar characteristics. Picó (2015) observed that PCA provides deeper insight into the data set and is useful to display patterns that are not always obvious.

The density of Antestia bug in both years of the study was high, ranging from 0 to 8 Antestia bugs per tree and 0 to 9 Antestia bug per tree, in 2016 and 2017, respectively. The economic threshold of this pest is as low as 1 to 2 bugs per tree, depending on the damage and on the country (Bigirimana et al., 2012; Ahmed et al., 2016). In the study, the economic damage ranged from 0 to 92% and from 0 to 81% in 2016 and 2017, respectively. These data suggest that there is an urgent need for Antestia bug control in some areas. Although two years is a short time for climate change assessment, temperature rise in East Africa has been reported (Jaramillo et al., 2011). This has benefited coffee berry borer, another worldwide coffee pest, which has increased its damage to coffee crops and expansion in the distribution range (Jaramillo et al., 2011). Expansion of the coffee production area was proposed in Rwanda, based on the spatial distribution of actual and potential production zones for Arabica coffee (Nzeyimana et al., 2014). Antestia bug may also expand its distribution range, following the newly planted coffee areas. Antestia bug prefers feeding on coffee, particularly Arabica coffee and its density increases with altitude (Ahmed et al., 2018). The impact of climate change on density and damage of Antestia bug as well as of other coffee pests need further research.

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References

Abebe, 1987. Insect pests of coffee with special emphasis on Antestia, *Antestiopsis intricata* in Ethiopia. Int. J. Trop. Insect Sci. 8, 977–980.
Ahmed, A.G., Murungi, L.K., Babin, L., 2016. Developmental biology and demographic parameters of antestia bug *Antestiopsis thunbergii* (Hemiptera, Pentatomidae) on *Coffea arabica* (Rubiaceae) at different constant temperatures. Int. J. Trop. Insects 36 (3), 119–127.
Ahmed, A.G., Pirk, C.W., Yusuf, A.A., Pinard, F., Niassy, S., Mosomtai, G., Babin, R., 2018. Prediction of insect pest distribution as influenced by elevation: combining field observations and temperature-dependent development models for the coffee stink bug, Antestiopsis thunbergii (Gmelin). PLoS One 13 (6), e0199569.
Aho, K., Derryberry, D., Peterson, T., 2014. Model selection for ecologists: the worldviews of AIC and BIC. Ecology 95 (3), 631–636.
Babin, R., Mbondji Mbondji, P., Mendesil, E., Mugo, H.M., Lee, J.-H., Serracin, M., et al., 2018. The antestia bug complex in Africa and Asia. In: McPherson, J.E. (Ed.), Invasive Stink Bugs and Related Species (Pentatomoidea): Biology, Higher Systematics, Semiochemistry, and Management. CRC Press, USA, pp. 465–493.
Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Good, J.E., 2002. Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. Glob. Chang. Biol. 8 (1), 1–16.
Becker, R.D., Nitz, B., S Vitzthum, Q.Z., 1988. Identification of the peasy off-flavour note in central African coffees report. In: 12. International Scientific Colloquium on Coffee29 Jun-3 Jul 1987Montreal (Canadá) (No. 633.73063 C714 1987). Association Scientifique Internationale du Café, París (Francia).
Bigirimana, J., Adams, C.G., Gatarayiha, C.M., Muhutu, J.C., Gut, L.J., 2019. Occurrence of potato taste defect in coffee and its relations with management practices in Rwanda. Agric. Ecosyst. Environ. 269, 82–87.
Bigirimana, J., Njoroge, K., Gahakwa, D., Phiri, N.A., 2012. Incidence and severity of coffee leaf rust and other coffee pests and diseases in Rwanda. Afr. J. Agric. Res. 7 (26), 3847–3852.
Bouyjou, B., Fourny, G., Perreaux, D., 1993. Le goût de pomme de terre du café arabica au Burundi. In: Proceedings of the 15th International Scientific Colloquium on Coffee, 6-11 June 1993, Montpellier, France. ASIC, Paris, France, pp. 357–369.
Foucart, G., Brion, L., 1959. Contribution à l'étude de la punaise du caféier Arabica au Rwanda-Urundi. ISAR, Butare, Rwanda, p. 334.
Gherlenda, A.N., Esveld, J.L., Hall, A.A., Duursma, R.A., Riegler, M., 2016. Boom and bust: rapid feedback responses between insect outbreak dynamics and canopy leaf area impacted by rainfall and CO2. Glob. Chang. Biol. 22 (11), 3632–3641.
Gueule, D., Fourny, G., Ageron, E., Le Flèche-Matéos, A., Vandenbogaert, M., Grimont, P. A.D., Cilas, C., 2014. *Pantoea coffeiphila* sp. nov. cause of 'potato taste' of Arabica coffee from African Great Lakes region. Int. J. Syst. Evol. Microbiol. 65, 23–29.
Hodkinson, I.D., 1999. Species response to global environmental change or why ecophysiological models are important: a reply to Davis et al. J. Anim. Ecol. 68 (6), 1259–1262.
Hughes, G., McKinlay, R.G., 1988. Spatial heterogeneity in yield-pest relationships for crop loss assessment. Ecol. Model. 41 (1–2), 67–73.
Jackels, S.C., Marshall, E.E., Omaiye, A.G., Gianan, R.L., Lee, F.T., Jackels, C.F., 2014. GCMS investigation of volatile compounds in green coffee affected by potato taste defect and the Antestia bug. J. Agric. Food Chem. 62 (42), 10222–10229.
Jaramillo, Juliana, Muchugu, Eric, Vega, Fernando E., Davis, Aaron, Borgemeister, Christian, Chabi-Olaye, Adenirin, 2011. Some like it hot: the influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa. PLoS One 6 (9), e24528.
Kirkpatrick, T.W., 1937. Studies on the ecology of coffee plantations in East Africa. II. The autecology of *Antestia* spp. (Pentatomoidea) with a particular account of a Strepsipterous parasite. Trans. Royal Entomol. Soc. 86, 247–343.
Le Pelley, R.H., 1968. Pests of Coffee. Longmans Green and Co Ltd, London, United Kingdom.
Lewis, T., 1969. The distribution of flying insects near a low hedgerow. J. Appl. Ecol. 443–452.
Liebhold, A.M., Rossi, R.E., Kemp, W.P., 1993. Geostatistics and geographic information systems in applied insect ecology. Annu. Rev. Entomol. 38 (1), 303–327.
Moser, D., Drapela, T., Zaller, J.G., Frank, T., 2009. Interacting effects of wind direction and resource distribution on insect pest densities. Basic Appl. Ecol. 10 (3), 208–215.
Mugo, H.M., 1994. Coffee insect pests attacking flowers and berries in Kenya: a review. Kenya Coffee 59, 1777–1783.
Mugo, H.M., J.K., Kimemia, J.M., Mwangi, 2013. Severity of antestia bug, Antestiopsis spp and other key pests under shaded coffee in Kenya. Int. J. Sci. Nat. 4 (2), 324–327.
Nzeyimana, I., Hartemink, A.E., Geissen, V., 2014. Gis-based multi-criteria analysis for Arabica coffee expansion in Rwanda. PLoS One 9 (10), e107449.
Overmars, K.P.D., De Koning, G.H.J., Veldkamp, A., 2003. Spatial autocorrelation in multi-scale land use models. Ecol. Model. 164 (2–3), 257–270.
Picó, Y., 2015. Mass spectrometry in food quality and safety: an overview of the current status. In: Comprehensive Analytical Chemistry, vol. 68. Elsevier, pp. 3–76.
Raykov, T., Marcoulides, G., 2008. An Introduction to Applied Multivariate Analysis. Routledge Taylor & Francis Group, 711 Third Avenue, New York, NY, p. 10017.
Rider, D.A., Zheng, L.Y., Kerzhner, I.M., 2002. Checklist and nomenclatural notes on the Chinese Pentatomidae (Heteroptera). II. Pentatominae. Zoosyst. Ross. 11, 135–153.
Teodoro, A., Klein, A.M., Tscharntke, T., 2008. Environmentally mediated coffee pest densities in relation to agroforestry management, using hierarchical partitioning analyses. Agric. Ecosyst. Environ. *125* (1–4), 120–126.
Verdoodt, A., Van Ranst, E., 2003. A large-scale land suitability classification for Rwanda. In: Land Evaluation for Agricultural Production in the Tropics. Laboratory of Soil Science, Ghent University, Belgium.
Waller, J.M., Bigger, M., Hillocks, R.J., 2007. Coffee Pests, Diseases and their Management. CAB International, Wallingford, UK, p. 434.
Wallner, W.E., 1987. Factors affecting insect population dynamics: differences between outbreak and non-outbreak species. Annu. Rev. Entomol. 32 (1), 317–340.
Williams, I.H., Frearson, D.J.T., Barari, H., McCartney, A., 2007. Migration to and dispersal from oilseed rape by the pollen beetle, Meligethes aeneus, in relation to wind direction. Agric. For. Entomol. 9, 279–286.
Zitko, V., 1994. Principal component analysis in the evaluation of environmental data. Mar. Pollut. Bull. 28 (12), 718–722.